LABORATORY FOR INFORMATION AND DECISION SYSTEMS
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

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GRAPHICAL, GEOMETRIC, AND LEARNING/OPTIMIZATION-BASED METHODS IN STATISTICAL SIGNAL AND IMAGE PROCESSING, OBJECT RECOGNITION, AND DATA FUSION

PRINCIPAL INVESTIGATOR: PROF. ALAN S. WILLSKY

Submitted to: Dr. Jon Sjogren
AFOSR/NE
Physics and Electronics
875 North Randolph Street
Suite 325, Room 3112
Arlington, VA 22203

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13. ABSTRACT (Maximum 200 words)

This report summarizes our accomplishments under this grant. Our research covers several interrelated areas: (a) the use of graphical, hierarchical, and multiresolution representations for the development of statistical modeling methodologies for complex phenomena and for the construction of scalable algorithms for the fusion of multiple heterogeneous sources of information; (b) the development of first principles methods for constructing statistical models for shapes and for the use of these models in developing robust and statistically optimal methods of shape estimation and recognition; and (c) the development of new statistical learning and optimization algorithms for feature extraction, signal and image restoration, and sensor fusion. Our research blends methods from several fields—statistics and probability, signal and image processing, mathematical physics, scientific computing, statistical learning theory, and differential geometry—to produce new approaches to emerging and challenging problems in signal and image processing, and each aspect of our program contains both fundamental research in mathematical sciences *and* important applications of direct relevance to Air Force missions. In particular, our research is relevant to automatic target recognition based on synthetic aperture radar and laser radar imagery; wide-area surveillance and information preparation of the battlefield; global awareness and higher-level fusion for situational assessment; and fusion of multiple heterogeneous sensors. In all of these areas we have contacts and interactions with AFRL staff and with industry involved in Air Force programs.

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I. Summary: Objectives and Status of Effort

In this report we summarize our accomplishments under the research program supported by Grant FA9550-04-1-0351. Our research covers several interrelated areas: (a) the use of graphical, hierarchical, and multiresolution representations for the development of statistical modeling methodologies for complex phenomena and for the construction of scalable algorithms for the fusion of multiple heterogeneous sources of information; (b) the development of first principles methods for constructing statistical models for shapes and for the use of these models in developing robust and statistically optimal methods of shape estimation and recognition; and (c) the development of new statistical learning and optimization algorithms for feature extraction, signal and image restoration, and sensor fusion. Our research blends methods from several fields—statistics and probability, signal and image processing, mathematical physics, scientific computing, statistical learning theory, and differential geometry—to produce new approaches to emerging and challenging problems in signal and image processing, and each aspect of our program contains both fundamental research in mathematical sciences *and* important applications of direct relevance to Air Force missions. In particular, our research is relevant to automatic target recognition based on synthetic aperture radar and laser radar imagery; wide-area surveillance and information preparation of the battlefield; global awareness and higher-level fusion for situational assessment; and fusion of multiple heterogeneous sensors. In all of these areas we have contacts and interactions with AFRL staff and with industry involved in Air Force programs.

The principal investigator for this effort is Professor Alan S. Willsky. Prof. Willsky is assisted in the conduct of this research by Dr. John Fisher, principal research scientist in Prof. Willsky's group, by Dr. Mujdat Cetin, research scientist in Prof. Willsky's group, by Dr. Sujay Sanghavi, a post-doctoral researcher in Prof. Willsky's group, and by several graduate research assistants as well as additional thesis students not requiring stipend or tuition support from this grant. In the next section we briefly describe our recent research efforts; in Section III we indicate the individuals involved in this effort; in Section IV we list the publications supported by this effort; and in Section V we discuss several other topics including honors received by researchers involved in this project, transitions, and plans for future transitions.

II. Accomplishments

In this section we briefly describe our research supported under this grant. We limit ourselves here to a succinct summary and refer to the publications listed at the end of this report for detailed developments. However, we do note here that our work continues to have significant impact, both in terms of DoD-related activities and transitions in progress (Section V) and in terms of recognition from the research community.

2.1 Graphical, Multiresolution, and Hierarchical Modeling and Fusion

The research described in this section is developed in great detail in a number of papers and reports [2, 6-7, 9-10, 12-14, 17-19, 23-24, 29-33, 35, 38, 43, 48-49, 55-63, 70-76, 83-89, 93-105]. The overall objective of this portion of our research is the development of methods for constructing stochastic models for phenomena that vary over space, time, and hierarchy and that possess structure which can be exploited to construct efficient and scaleable algorithms for statistical inference.

a) During the past year we have continued our development of so-called *walk-sum analysis* for inference in Gaussian graphical models. As described in last year's report, walk-sum analysis represents an expansion of the set of information made available to a node through successive message passing throughout a graphical model (so that messages engage in "walks" throughout the network during which they are modified at each node, so that information is accumulated in the process). Using this interpretation, we have a precise characterization of the gap between what Belief Propagation computes for error variances in Gaussian models and what the exact computation should produce. This interpretation leads to the tightest known sufficient conditions for BP convergence as well as to a deep understanding of when BP fails. Moreover, this walks-sum analysis has provided the basis for the solution of a long-standing open problem, namely the development of easily checked conditions for the convergence of our previously developed Embedded Trees algorithm. In addition, this work also provides the basis for an adaptive method for choosing which updates should be considered at each stage in the iteration, where the criterion used measures the incremental value-added of each option. This idea has far broader implications, e.g., for sensor resource management and in other powerful algorithms that we have developed.

b) New for this year is another emerging class of algorithms based on Lagrangian relaxation. In this approach an overall graphical model is decomposed into a set of models each on a tractable subgraph of the original graph. Inference is then performed subject to the constraint that the estimates produced on all of these subgraphs agree. Adjoining these equality constraints via Lagrange multipliers leads to iterative algorithms in which estimates are computed on all graphs followed by modifying the decomposition to drive the estimates toward equality. In addition to guarantees of convergence for estimates, this approach also yields

upper bounds on error variances which can be further tightened by optimization of the weighting used in the decomposition. We view this approach as the start of a very powerful and rich approach to inference that we expect to develop further in the future.

c) We have also continued our research on what we refer to as low-rank variance estimation methods for complex graphical models. The idea behind this approach is to construct low-rank approximations to the identity matrix (!) with particular properties. Such a representation leads directly to an estimate of the variance at every node in the graph corrupted by "interference" from the cross-correlation between pairs of nodes and the dot product of the corresponding rows in the low-rank approximation to the identity. These leads to the idea of choosing the approximation to have orthogonal rows when cross-correlations are large but not worrying about their non-orthogonality if the corresponding cross-correlation is negligible. This leads to interesting graph-coloring algorithms for designing these overcomplete sets of rows, and, together with randomized choices of signs on these rows, we obtain unbiased estimates of the exact variances with guaranteed accuracy for processes with exponentially decaying correlations. For processes with long-distance correlations a variation on this approach using wavelets – and what we refer to as *spliced wavelet bases* – yields equally powerful methods for an even richer class of processes. Extension to problems involving the fusion of multiresolution data is a promising direction for the future.

d) We have made significant process on a line of research that has already yielded important results and offers much more for the future. The focus of this work is on the building of thinned and thus more tractable graphical models that accurately approximate the statistics of more complex models. Specifically, if we attempt to build graphical models with maximum entropy whose statistics *exactly match* those of a specified graphical model, we will, in general obtain complex models. However, if we *relax* the constraints—i.e., if we only require that the statistics of our simpler model be close to those of the more complex one—the resulting max-entropy model is frequently dramatically simpler. We have a first paper on this work that demonstrates the model-thinning power of this approach and we are now considering its extension to problems involving *adding* hidden variables in ways in which we can then perform thinning on this expanded model. This is of particular importance in the context of multiresolution modeling (see the next topic).

e) We have now completed a first investigation of a new class of Gaussian models on pyramidal graphs – ones in which each level in the pyramid is itself a graphical model but in which there are also inter-scale interconnections. Such models are capable of capturing long-distance correlations but without the serious artifacts arising from models defined on multiscale trees. However, these models are defined on graphs with many loops, something that has led in the past to very complex algorithms Thanks to the properties of these models and their other properties, we have overcome these difficulties and produced a very powerful suite of algorithms. One such algorithm results from another very important property of these models, namely that the *conditional* correlation within any scale, when conditioned on its coarser- and finer-scale neighbors, is dramatically

compressed. This leads to algorithms reminiscent of multipole algorithms for the solution of PDEs in which coarse-scale estimates are corrected by local in-scale computations. Indeed using walk-sum analysis as described previously, not only have we developed efficient algorithms with this structure that are guaranteed to converge but we have used the methods for adaptive choice of embedded subgraphs mentioned previously to achieve very rapid convergence. Moreover, these methods can also be adapted to the very important problem of *re-estimation,* i.e., rapid recomputation of estimates to incorporate new data. Such problems arise in complex mapping applications –e.g., the incorporation of new terrain elevation data into existing maps. In addition, these algorithms are perfectly suited to the Lagrangian relaxation methods described previously and to the very accurate low-rank variance estimation methods, a property that we have exploited not only for efficient estimation but also for rapid parameter estimation.

f) A very recently-initiated research direction is that of learning tractable graphical models from data, where the criterion used is not model accuracy but *model utility* – in particular the error exponent in discriminating between two high-dimensional probability distributions. As one would expect, if vast amounts of data are available, the models learned for the two different probability distributions revert to the best models for each individually. However, when data are limited, the results can be significantly different. This is of potentially great value in many contexts in which high-dimensional data need to be processed but sufficient data are not available to build accurate models (or building such models is computationally intractable). Applications ranging from hyperspectral data analysis to multimodal fusion for object classification will benefit from this line of research.

g) We have also initiated new efforts on discrete optimization problems specified on graphical models, with initial focus on the so-called maximum independent set and matching problems. Such problems arise in a variety of applications including many involving resource management and optimization. Such problems are naturally cast as integer programming problems which are NP-hard. Relaxed versions of these problems can be formulated in terms of linear programs. Such a formulation can lead to integrality gaps and thus fail to give optimal answers; however in some cases the LP does indeed yield optimal solutions. Alternatively these problems can be formulated as MAP estimation problems on graphical models for which the so-called max-product algorithm provides a general purpose algorithm that is only guaranteed to yield optimal answers for graphs without loops but often works well in other contexts. We have made considerable progress in relating LP and max-product approaches, providing both conditions under which either or both are guaranteed to yield optimal estimates as well as new algorithms.

h) During this past year we have continued our work on a very new class of graphical models motivated by problems in object recognition (see Sec. 2.2) in which we have considerable uncertainty about the numbers of features associated with each part of an object, the numbers of parts comprising an object, the numbers of types of objects, and the numbers of instances of each object type in the scene being surveilled. To attack these complexities we have built on the

framework of so-called Nonparametric Bayesian Methods exploiting so-called Dirichlet processes (and their extensions) which allow us, in a simple manner, to capture ambiguities and uncertainties at the level of granularity of the numbers of "things"—features, parts, objects, etc. We have demonstrated the power of this method in the context of object recognition, and have now initiated an effort to exploit this framework for problems of learning dynamic models for the motion of non-cooperative targets.

i) One of the important areas of application and development of efficient graphical inference algorithms is multisensor, multitarget data association, a notoriously complex problem. In previous years we had demonstrated that our new approach to so-called max-product and tree-reweighting inference algorithms could yield remarkably efficient solutions to optimal data association problems. In addition, with an eye toward implementation in distributed sensor networks, we developed a local, adaptive version of TRP and belief propagation algorithms in which, at each iteration, each node can decide whether to transmit a message to each of its immediate neighbors based on whether the potential new message differs in a statistically significant manner from the previous message that was sent to that neighbor. Last year we showed that this locally adaptive algorithm can result in dramatic reductions in computations—and communications, if these messages were indeed sent through a sensor network—with minimal decrease in association performance. In recent work we have extended these ideas to full temporal multi-object tracking and data association, using ideas from Nonparametric Belief Propagation (discussed next) to devise novel and efficient algorithms to achieve scalability and overcome the combinatorial explosion inherent in exact multi-target tracking. We believe that this opens the door to extremely powerful new methods which we are just beginning to explore, using these new graphical representations as well as incorporating the emerging methods mentioned in item (h) involving Dirichlet processes to deal with unknown numbers of objects or more complex situations in which groups of objects are moving as clusters (e.g., convoys, formation flying) but we don't know how many clusters there are or how many (and which) objects are in each cluster.

j) As the preceding item illustrates, we have continued to exploit our approach to inference for graphical models that involve non-Gaussian densities—problems of particular importance for various sensing modalities that provide measurements of either bearing or range. These methods, which involve the use of methods for nonparametric density estimation (for which reason we refer to them as *Nonparametric Belief Propagation (NBP)* algorithms), can be viewed as extensions of concepts of particle filtering to inference on graphs—this extension is highly nontrivial, especially for graphs with loops, as the iterative computations and generation of messages of belief propagation require new ideas for generating "particles" to replace those messages. In addition to developing the basic methodology, we have demonstrated its power in several very different contexts including the target tracking application mentioned in the preceding paragraph, source localization in sensor networks, the computer vision application of hand-tracking in video sequences (see Section 2.2), machine learning approaches to

object and scene recognition (see Section 2.2), and tracking of dynamically evolving shapes of objects (see Section 2.2).

k) As we described last year, motivated by issues of communications-constrained sensor network operation we have investigated two separate problems, with considerable success in each. In the first of these we have examined the impact of errors in message passing algorithms (where the errors might result from "message censoring" as discussed in the context of target tracking in paragraph (c); or they might result from message quantization). By introducing a new dynamic range measure of error, we have been able to develop both bounds and stochastic approximations on the propagation of errors in belief propagation algorithms. In addition, this analysis also had yielded the best known sufficient conditions for the convergence of belief propagation in loopy graphs. In addition, we have completed a study of efficient computation of particle-based messages, combining information-theoretic concepts with our NBP algorithmic structure. In particular, since the order in which particles are transmitted is irrelevant, we have developed a very efficient multiresolution representation of such methods that allows very efficient coarse-to-fine coding and transmission as well as a very effective framework for trading off accuracy of message transmission (i.e., the level of granularity of the transmitted representations) with overall inference quality, providing a tie directly between communication constraints on bit rates and overall fusion accuracy.

l) We have also made significant progress in an investigation that brings together the field of decentralized team decision-making and message passing algorithms on graphs. In particular, for the case of a directed set of sensing, decision, and communication nodes (so that each node receives its own measurements together with bits from its "parent" nodes and then makes decisions resulting in bits transmitted to its "children") we have shown that so-called person-by-person team optimization can be achieved via a message passing algorithm. This emphasizes that in communication-limited contexts with distributed agents, the agents must *organize* themselves and, in particular, design communication *protocols* for the generation and interpretation of messages within the agent network. We have now written an extensive paper on this work and demonstrated its value in designing decision networks that may differ in structure from that of the underlying variables being estimated. Moreover we have begun to develop an undirected version of this framework – a nontrivial extension as such a framework in principle allows feedback so that making a decision on what to communicate must also be based on the impact that that communication will have on what will be communicated *back* to the transmitting node.

m) We have also developed a new, first principles probabilistic approach to Markov modeling on trees, together with a start on the nontrivial generalization to graphs with loops. Interestingly this approach identifies reduced sets of conditional independence relationships that need to be verified either in determining if a particular set of variables are Markov or in *designing* hidden variable representations to ensure Markovianity. The former interpretation of our results is of great importance in the context of the estimation of the *structure* among a set of observed variables—e.g., to identify statistical links among them as well as

conditional independencies, a topic sometimes referred to as *link discovery.* The latter interpretation is of importance in building graphical models with tractable structure, possibly by incorporating hidden variables, in order to adequately approximate the statistical relationships among a set of variables of interest.

2.2 Geometric Modeling, Shape Estimation, and Object Extraction and Recognition

The research described in this section deals with efficient algorithms for large-scale optimal estimation and is reported in detail in [3,5,11,15-16,22,26, 36-37, 39, 41, 46-47, 58-59, 70-71, 92]. The general objective of this part of our research is the development of statistically robust methods for segmentation, shape estimation, and object recognition. Much of our work in this area has focused on so-called curve evolution methods and, in particular, on developing statistically-based curve evolution algorithms. However, we now also have some research that exploits ideas from graphical models described in the preceding subsection:

a) The use of particle-based methods as in NBP leads naturally to the question of using Monte Carlo methods to sample from curve/shape distributions directly—i.e., to generate "particles" that correspond to complete curves. We have now developed a methodology for doing this – a nontrivial development as the use of Metropolis-Hastings algorithms required developing so-called *detailed balance* acceptance rules that are needed to guarantee that samples are generated by the desired shape distribution. We have also developed methods for displaying the uncertainty in the resulting extracted shapes – a feature that we believe will be of great importance in object recognition applications. One of the appealing aspects of this sampling framework is that, with the detailed balance issue now solved, it is relatively easy to include features in the distribution that are easily used for acceptance-rejection of samples but are not easily incorporated into curve evolution methods. Several papers are in progress.
b) One of the major areas of our current and future research in this area is that of incorporating prior information about shape into curve evolutions. This is particularly important for problems in which image SNR is low or in which the objects of interest are partially occluded. Major issues here include the development of methods for constructing prior probability distributions on shapes from examples and the incorporation of these priors into curve evolution formalisms. Our initial work in this area used a set of training examples to construct a set of "eigenshapes," which then are used to provide a *linear* parameterization of a set of shapes, where the parameters of that linear parameterization is then estimated as part of the curve evolution process. Results on both military and medical images in both 2-D and 3-D have demonstrated that this methodology has a great deal of promise. In addition, we have been working to move beyond these linearly-parameterized methods in several different directions. The first of these methods involves postulating that the model to be learned from training examples is a mixture of two or

distributions each of which is well characterized by principal component analysis. This introduces a hidden variable for each training sample—i.e., the component of the mixture to which it corresponds—which in turn leads to a new EM-based algorithm. Results demonstrate the power of this extension to classify shapes and model their variability. A second approach we are taking is that of learning nonparametric models for shapes given a set of training samples. Nonparametric density estimation methods require the use of a distance metric between pairs of shapes, and our work has led us to use two natural metrics, each of which leads to a different curve evolution. Both of these have been shown to have considerable promise for recognizing and segmenting shapes that can have considerable variability or be subject to partial occlusion. We are also developing new methods that can incorporate human or expert input – e.g., in the form of partial segmentations – to help guide both curve evolution as well as Monte Carlo sampling.

c) We have also made major progress on the development of methods for space-time tracking of curves or boundaries that evolve in time themselves. Our approach to this problem involves developing and exploiting models for the probabilistic evolution of such curves—in essence developing temporal Markov models for these curves. Our approach combines (i) the idea of using low-dimensional parameterizations of curves (e.g., using principal components); (ii) information-theoretic methods to learn nonparametric statistical models for the dynamics of those parameterizations; (iii) non-parametric belief propagation to exploit these dynamic models for the tracking of curves; and (iv) curve evolution methods based on level sets. Very promising results have been obtained in a soon-to-be-completed Ph.D. thesis.

d) Our work on NBP has found its way into a line of inquiry not involving curve evolution methods, namely direct tracking of objects that have constrained motion (such as articulation of limbs, etc.), using graphical models to capture these constraints. The surrogate application used in this study is that of hand-tracking, and we have had good success in developing methods that are superior to those previously developed.

e) Finally, the work described in the preceding section on Dirichlet processes has provided the basis for machine learning methods to learn graphical models for scenes, objects and parts—i.e., to learn relationships among these with very limited *a priori* information. This is a very powerful approach to building complex models and one that we believe is just the tip of the iceberg—e.g., our current approach uses fixed feature extraction methods for video imagery and then builds models based on these features. More sophisticated approaches—and ones that tie in well with our work on wide-area SAR described in the next section—would involve feedback in that the front-end feature extraction required might depend on the likely hypotheses for the objects in the scene being imaged.

2.3 Machine Learning and Optimization Methods for Signal and Image Processing, Fusion, and Feature Extraction

The research described in this section deals with methods for complex signal, image, and data analysis using methods of machine learning and optimization- based formulations. Our research is described in [1-2, 4, 8, 14, 21, 27-28, 34, 30, 42, 44-45, 50-54, 66-69, 77-83, 90-92, 105-107]. Our research has led to the following lines of inquiry and results:

a) An area in which we have made considerable progress this year is that of blending nonparametric estimation methods (such as particle filtering) together with learning-based optimization algorithms (e.g., approximate dynamic programming) to examine challenging and important problems in sensor resource management. We have had considerable success in developing methods in several directions including: (i) switching among multiple sensing modes—a problem of great importance in exploiting multi-modal radar; (ii) switching field of regard for a sensor (i.e., deciding when to look where); (iii) dealing with limited communications in designing near-optimal systems for tracking and track hand-off in sensor networks; and, most recently, (iv) developing bounds on the performance loss in using tractable suboptimal strategies as opposed to truly optimal (but not computable) ones. A number of conference and journal papers have been written or are in progress.
b) Our work on learning object dynamics using Hierarchical Dirichlet processes represents a new thrust for our research on learning models for complex dynamic phenomena. We have also continued our work on exploiting ideas from nonparametric statistics, information theory, and machine learning for the construction of dynamic models from complex signals in an unsupervised learning context. The principle we have adopted in this and in our other work in this area is that of maximizing mutual information. In particular, in this context, the objective is to identify functionals of the past of a signal that have maximal mutual information with the next value of the signal. In the process of performing that optimization using nonparametric statistical methods, we also build a model for the transition probability for the process, i.e., the conditional pdf for the next value of the signal given these maximally informative functionals of the past. This pdf, then, serves as a *dynamic model* of the phenomenon which can be used for signal prediction, simulation, discrimination, and estimation. As discussed in Section 2.2, this method is now finding application in our work on tracking dynamically evolving shapes. In addition, we are using these methods in order to detect and identify statistical links among multiple data streams (e.g., audio and video). These methods relate closely to the ideas mentioned in Section 2.1, item (i) for determining the statistical links among multiple variables.
c) A continuing and very active component of our research focuses on variational methods to produce enhanced images and reconstructions for SAR, ISAR, and more general array processing applications. In particular, by putting particular penalties (e.g., L_p, with $p < 1$) either on the reconstructed image or on the gradient of the reconstructed image, we have shown that we

can produce remarkably sharp images of point scatterers or regions and can also correct for phase errors due to target motion—an extremely important problem in SAR imaging of moving targets or to other sources (including timing errors to array element location errors). Moreover, in contrast to many other superresolution methods (e.g., MUSIC, Capon's method), our method can resolve multiple scattering effects that are highly correlated—e.g., due to the presence of multipath effects. In one part of our recent research we have developed new variational approaches for array processing that work well for broadband sources and, in particular, for sources that generate multiple harmonics (e.g., as are present in any motor or machinery). In other parts we have developed new methods for coherent imaging for wide-aperture and wide-but-sparse aperture SAR that have attracted considerable interest from AFRL/SN.

d) In this last part of our research we have taken a deeper look at marrying SAR physics with nonparametric statistical learning methods for constructing probabilistic models for multiresolution imagery. In particular consider the formation of SAR imagery based on a given full aperture of data. If we use the entire aperture, we obtain imagery at the finest resolution resolvable using that data. However, to do this we in essence must assume that all scattering is isotropic, i.e., that the response from significant scatterers is constant across the entire aperture. For many important scattering mechanisms this is not the case at all, and this anisotropy is critical to distinguishing one scatterer type from another. Suppose then, that in addition to forming an image using the entire aperture, we also form three images each using half of the aperture: one image using the right half, one the left, and one using a centered half-aperture. If indeed there are anisotropic scatterers, we might expect that there would be differences in the responses in each of these half-apertures and hence in the images formed using them (note that these images would have pixel sizes twice as large as the ones in the finest scale imagery). Iterating this process, we can imagine forming a vector of images at each of a sequence of scales corresponding to progressively smaller subapertures. By looking across scale, then, we would expect not only to find statistical variability due to speckle but also any evidence of anisotropic scattering manifesting itself in statistically significant differences in pixel intensities in images formed using different subapertures. During the past year we have initiated a new effort in this area that employs the "sparseness prior" variational framework described in the preceding paragraph. Initial results provide the basis for some new "best basis" methods for imaging that avoid exhaustive search of subapertures through a modified coarse-to-fine search with intelligent back-tracking. We believe that there is much more that can be done in this area. For example, one very promising direction for future work is that of coupling these front-end algorithms with back-end object recognition using the framework of Dirichlet processes for object recognition described in the preceding section. In particular, we expect that by building object models that couple object models with anisotropy properties we will be able to develop algorithms in which object-level hypotheses will drive front-end signal processing. This

offers the possibility of a significant conceptual and algorithmic leap over current methods (e.g., the current form of the so-called "PEMS Loop" in the algorithms developed under the MSTAR program).

III. Personnel

The following is a list of individuals who have worked on research supported in whole or in part by the Air Force Office of Scientific Research under Grant FA9550-04-1-0351:

Prof. Alan S. Willsky, Edwin Sibley Webster Professor of Electrical Engineering, MIT
Dr. John Fisher, SeniorResearch Scientist, MIT Comp.Sci. and AI Laboratory
Dr. Mujdat Cetin, Research Scientist, MIT Lab. For Information and Decision Systems
Dr. Sujay Sanghavi, Post-doctoral Researcher, MIT Lab. For Info. and Decision Systems
Dr. Dewey Tucker, graduate student (Ph.D. completed previous year)
Dr. Erik Sudderth, graduate student (Ph.D. completed previous year)
Dr. Junmo Kim, graduate student (Ph.D. completed previous t year)
Dr. Alex Ihler, graduate student (Ph.D. completed previous year)
Dr. Walter Sun, graduate student (Ph.D. completed previous year)
Dr. Jason Williams, graduate student (Ph.D. completed previous year)
Dr. Ayres Fan, graduate student (Ph.D. completed this year)
Mr. O. Patrick Kreidl, graduate student (Ph.D. completed this year)
Ms Emily Fox, graduate student
Mr. Jason Johnson, graduate student
Mr. Lei Chen, graduate student
Mr. Dmitry Malioutov, graduate student
Mr. Venkat Chandrasekaran, graduate student
Ms Myung Jin Choi, graduate student
Mr. Kush Varshney, graduate student
Mr. Vincent Tan, graduate student

IV. Publications

The publications listed below represent papers, reports, and theses supported in whole or in part by the Air Force Office of Scientific Research under Grant FA9550-04-1-0351:

[1] A. Ihler, J.W. Fisher III, and A.S. Willsky, "Nonparametric Dynamical Modeling with Applications to Signature Authentication," in preparation for submission to *IEEE Trans. on Signal Processing.*

[2] A. Ihler, "Inference in Sensor Networks: Graphical Models and Particle Methods," Ph.D. thesis, February 2005.

[3] J. Kim, "Nonparametric Methods for Image Segmentation and Shape Analysis," Ph.D. thesis, January 2005.

[4] M. Cetin, W.C. Karl, and A.S. Willsky, "A Feature-Preserving Regularization Method for Complex-Valued Inverse Problems with Applications to Coherent Imaging," *Optical Engineering,* Jan. 2006 (paper 017003).

[5] J. Kim, J.W. Fisher, III, A. Yezzi, Jr., M. Cetin, and A.S. Willsky, "A Nonparametric Statistical Method for Image Segmentation Using Information Theory and Curve Evolution," *IEEE Trans. on Image Processing,* Vol. 14, No. 10, Oct. 2005, pp. 1486-1502.

[6] M.J. Wainwright, T.S. Jaakkola, and A.S. Willsky, "A New Class of Upper Bounds on the Log-Partition Function," *IEEE Trans. on Information Theory,* Vol. 51, No. 7, July 2005, pp. 2313-2335.

[7] M.J. Wainwright, T.S. Jaakkola, and A.S. Willsky, "MAP Estimation Via Agreement on Trees: Message Passing and Linear Programming Approaches," *IEEE Trans. on Information Theory,* Vol. 51, No. 11, November 2005, pp. 3697-3717.

[8] A. J. Kim, J. W. Fisher III, and A. S. Willsky, "Multiresolution/Multiaperture Algorithms for Characterizing and Imaging Anisotropy in SAR Imagery," in preparation.

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V. INTERACTIONS/TRANSITIONS

In this section we summarize our recent interactions and plans for transitions associated with research supported by AFOSR Grant FA9550-04-1-0351, as well as listing some important honors received by members of our research team.

Honors

(1) Dr. Alexander Ihler received two separate Outstanding Student Paper Awards, one for his work on localization in sensor networks [31] and one for his work on message errors in belief propagation [33].
(2) Prof. Alan Willsky received an Honorary Doctorate from Université de Rennes (France) in October 2005. Prof. Willsky is one of two individuals receiving this degree as part of the celebration of the 25th anniversary of the founding of IRISA (Institut de Recherche en Informatique et Systèmes Aléatoires). A two-day workshop in honor of the recipients will be held.
(3) Mr. Lei Chen received the Outstanding Student Paper Award at the Fusion 2005 Conference in the summer of 2005.
(4) Mr. Jason Williams was also awarded the Outstanding Student Paper Award at Fusion 2005.
(5) Mr. Dmitry Malioutov and Mr. Jason Johnson received the Outstanding Student Paper Award at ICASSP 2006.

Participation/Presentation at Meetings

In addition to the many invited and contributed talks presented at various meetings during the past year, we also make note of the following:

(1) Prof. Willsky delivered a plenary lecture at the Annual Review Meeting of the Sensing and Signals Program of AFOSR, held at NC State University in May 2005.
(2) In October 2005 Dr. Cetin delivered an invited lecture at the Workshop on Imaging from Wave Propagation at the Institute for Mathematics and its Applications (IMA) as part of IMA's Thematic Year on Imaging.
(3) Prof. Willsky was the Washington University John Zaborszky Distinguished Lecturer for 2005-6 and delivered a series of lectures in February 2006.
(4) Prof. Willsky gave an invited lecture in February 2006 as part of the University of Michigan's Dept. of Electrical Engineering Distinguished Lecture Series.
(5) In May 2006 Prof. Willsky gave an invited lecture in Stanford University's Broad Area Colloquium on Artificial Intelligence.
(6) In October 2006 Prof. Willsky gave an invited lecture in the seminar series at the Dept. of Electrical Engineering, University of Connecticut.
(7) In April 2007 Prof. Willsky gave an invited lecture on large-scale, scalable data assimilation from remote sensing data at the IEEE – GEOSS Workshop, Honolulu, HI.

Consultative and Advisory Functions

We continue to be actively engaged in a number of activities relevant to the research being performed under our AFOSR grant:

(1) Prof. Willsky has regularly acted as a consultant to BAE Systems Advanced Information Technologies (BAE-AIT; formerly Alphatech, Inc.) in a number of research projects including ones that represent direct transitions of the technology being developed under our AFOSR Grant.
(2) Prof. Willsky is serving on the Senior Review Panel for DARPA's POSSE (Persistent, Operational Surface Surveillance and Engagement) Program which is aimed at rapid deployment of advanced ISR systems to active areas of conflict (note that all of the other members of the panel are either retired 3- and 4-star generals or individuals who previously served as Deputy Assistant Secretaries of Defense).

Transitions

The following represent some of the ongoing transitions of our work as well as some plans for future transitions:

(1) Our work on inference for graphical models—and especially our work on NBP, and error analysis for belief propagation algorithms—have been transitioned to MIT Lincoln Laboratory. There are a number of programs at Lincoln that are exploiting our research, but the most concentrated effort involves transition to programs in missile defense including target tracking and discrimination. The points of contact at Lincoln are Dr. Keh-Ping Dunn and Dr. David Choi.

(2) Our work on sensor resource management is also being transitioned to Lincoln Laboratory where it is also finding application in missile defense programs. The point of contact again is Dr. Dunn.

(3) Our efficient methodology for multiresolution mapping and data fusion have been transitioned to BAE-AIT as part of several programs on fusion of multiresolution and multipass data to produce high-fidelity terrain maps. The point of contact for this work at BAE-AIT is Dr. Alan Chao.

(4) Transition of our graphical estimation and optimization methods to BAE-AIT for several programs. Most recently, Prof. Willsky has been engaged with Dr. Mark Luettgen, who heads AIT's Fusion Technology and Systems Division, in transitioning these methods to programs in distributed multisensor fusion and detection, estimation, and tracking of terrorist networks.

(5) Dr. Mujdat Cetin has worked directly with Dr. Eugene Lavely of BAE-AIT on transitioning his sparse regularization methods to problems in radar signal processing and image formation.

(6) Dr. Mujdat Cetin's methods for sparse regularization for radar signal processing and SAR analysis have been transitioned to AFRL/SN, and Dr. Cetin, in collaboration with Prof. Randy Moses of Ohio State University have been working toward enhancing this transition. In addition, Dr. Cetin was recently awarded an AFRL grant under the RASER program to transition his methods to wide-aperture SAR image formation and analysis.

(7) Our work on new graphical model methods for target tracking and for object recognition are being transitioned to Lincoln Laboratory through one of our students, Emily Fox, who is working with Dr. Keh-Ping Dunn and Dr. David Choi of Lincoln.